THE WIND PROFILE AT THE CREST OF A LARGE RIDGE

HAROLD S. AYER

U.S. Weather Bureau, Portland, Oreg.

[Manuscript received September 9, 1959; revised December 21, 1959]

ABSTRACT

A set of observations of hourly wind movement at four levels in the layer 2–14 m. above the crest of a ridge is presented. The data are classified into prevailing wind types. During most periods the profile conforms to observations in flat terrain only in its lower part, and it does not conform to a normal structure of the free air. It is suggested that the observed profile represents an incompletely developed turbulent profile due to a short fetch over the ground surface.

1. INTRODUCTION

There have been a large number of investigations of the vertical profile of velocity near the ground, including many programs of measurements on towers or masts over flat or rolling terrain. There has been comparatively little in the way of precise observations above elevated terrain features.

The characteristics of the speed profile on ridge tops are of interest in regard to problems of anemometer exposure and comparison, and in relation to the general field of studies of the effect of topography on wind. In particular, it would be of interest to know the degree to which the profile resembles the profiles observed in flat terrain and the extent to which it varies with diurnal changes in thermal stability. Aerodynamic theory, as applied to the effects of topography, can be refined to more realistic models when the behavior in the "surface boundary layer" is known.

2. OBSERVATIONS AND ANALYSIS

In a field study in southwestern Washington, recorded data were obtained at levels 2.4, 4.0, 7.0, and 13.9 meters above the top of a ridge which is oriented north-south. The elevation of the ridge top is 875 m. and the local relief from valley to crest is about 450 m.; the ridge has the sharpest crest and the steepest slopes in the area. The site is near the foot of the western slope of the Cascade Range. Figure 1 shows the terrain profile near the crest. The pitch of the east-facing slope is quite similar to that of the west-facing slope. It is perhaps also of importance, in orienting this particular set of observations, to note that wind from almost all directions is subject to flow over other major ridges and valleys before reaching the site.

The ground cover varied from bare ground to bushes and bracken fern 0.5–1.0 m. in height, scattered clumps of trees about 3 m. in height, and a few conifers 9–15 m. The trees were not close enough to constitute obstructions to the instruments. Because of the irregular ground cover it is probably meaningless to define a friction surface.

Robinson three-cup anemometers were used. A comparison test was run with the anemometers side by side for a total of 1,600 km. of wind; the lowest and highest totals registered were within 3 percent of one another and no correction factors have been applied except for the standard calibration. There is a question of possible instrumental error due to nonhorizontal flow past the cups. The departure from the horizontal could not exceed the pitch of the ridge slopes, which is about 25°, and was probably much less. Wind tunnel tests [1, 2] have shown that errors in measurement of wind flow at incident angles of less than about 20° are negligible, and nonhorizontal flow is not considered to be a significant factor in the speed data obtained here.

Observations were recorded from September 15 to October 20, 1958. Direction recordings of 60 counts per

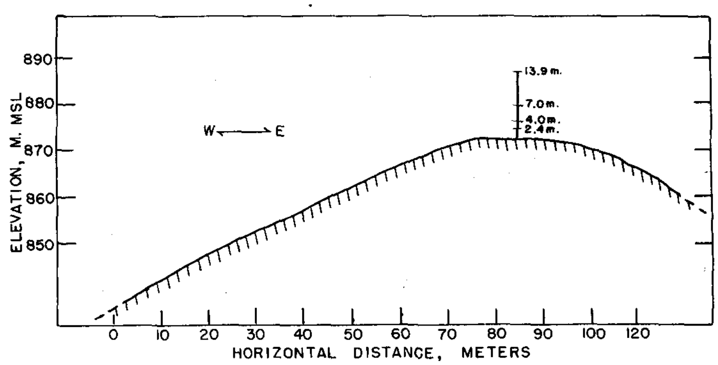

FIGURE 1.—Vertical section through the ridge near the crest. Vertical and horizontal scales are the same; the heights of anemometers are to scale.

541417—60——4

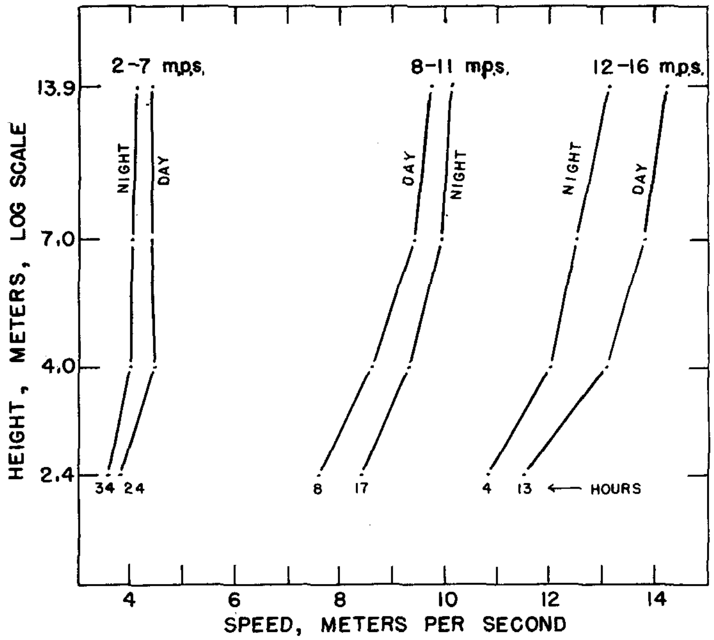

FIGURE 2.—Vertical profiles of speed at ridge top during fair-weather east winds (068°–113°).

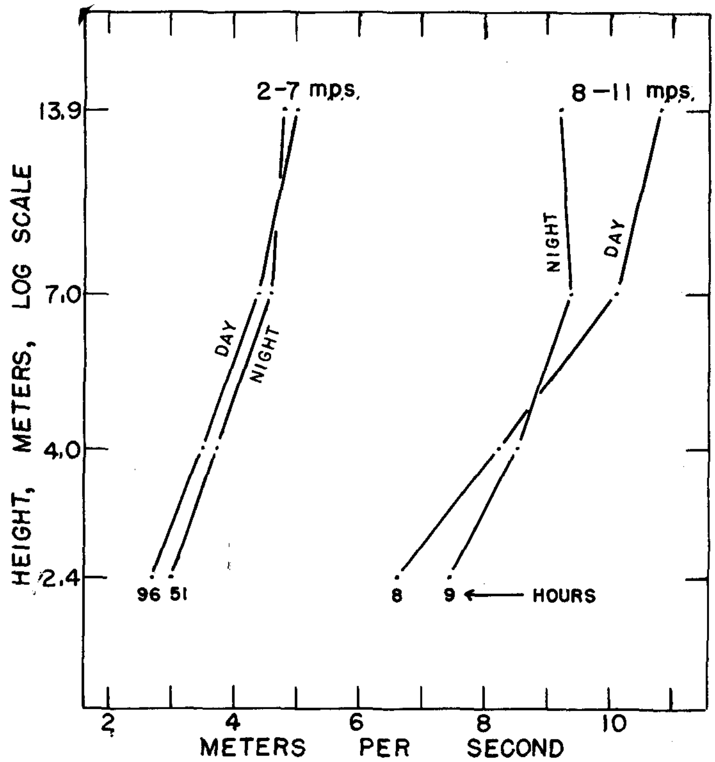

FIGURE 3.—Vertical profiles of speed at ridge top during fair-weather west winds (248°–293°).

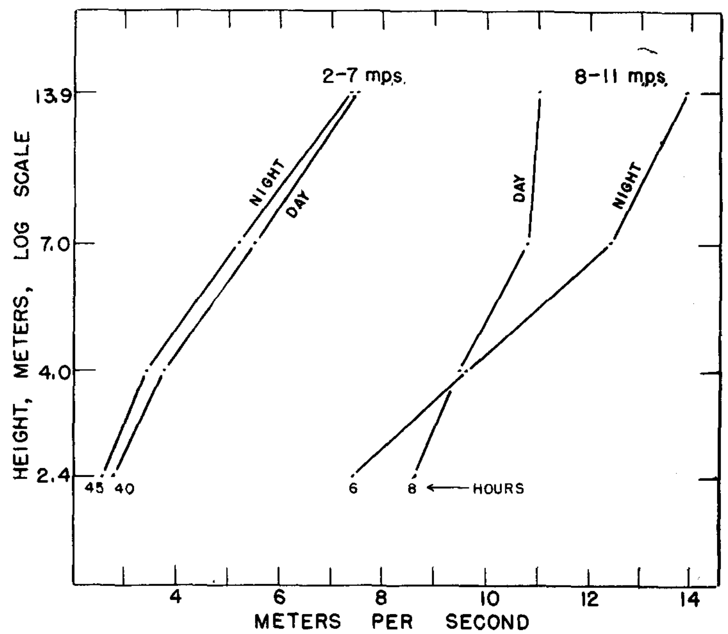

FIGURE 4.—Vertical profiles of speed at ridge top during rainy-weather westerly winds (203°–338°).

hour were obtained at the mast top. Frequent visual comparisons of directions at mast top and at 2.4 m. revealed no systematic variation. Speed data were tabulated as hourly totals of wind movement.

The data were separated into fair-weather periods and rainy periods. This selection is partly a subjective process, but the separation was considered desirable because rainfall has a pronounced effect on lapse rates and hence wind structure. The rainy periods consisted entirely of winds with a westerly component. The remaining westerly winds, classified as fair-weather winds, were sometimes accompanied by stratus or stratocumulus. The easterly winds, however, were accompanied by near-zero cloudiness. North and south winds were too light and infrequent to be representative and were discarded. The prevailing direction for each hour was tabulated to eight compass points. Hours when no single direction prevailed more than 50 percent of the time were discarded. Thus three general wind classes are treated: rainy westerlies, fair-weather westerlies, and fair-weather easterlies. Each of these is stratified by speed ranges and by daytime or nighttime hours. Hours when speeds were less than 2.2 m.p.s. at 4 m. on the mast were discarded in order to avoid erroneous values due to anemometer torque at near-calm conditions. The stratification of speeds was based on speeds at 4 m.

Figure 2 shows the profiles for the east winds. These are based on hours when the direction at 13.9 m. was due east. Figure 3 shows the profiles for fair-weather west winds. Prevailing northwest and southwest winds were treated separately, and although the hours of data are less the general features of the curves are similar. The data for daytime in the 8–11 m.p.s. range are almost entirely from one day and may not be a representative sample. In general, the shapes of the curves are similar to those for east winds, a principal difference being a greater slope within most of the strata (herein "greater slope" means greater increase of speed with height).

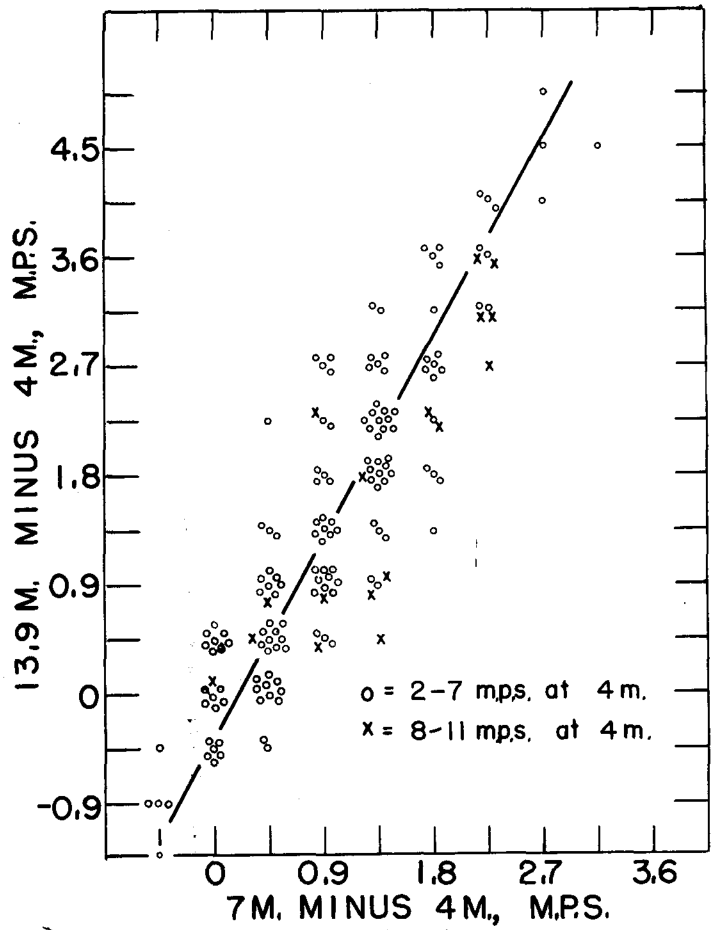

FIGURE 5.—Individual hourly differences in speed in the height interval 4.0–13.9 m. for fair-weather west winds.

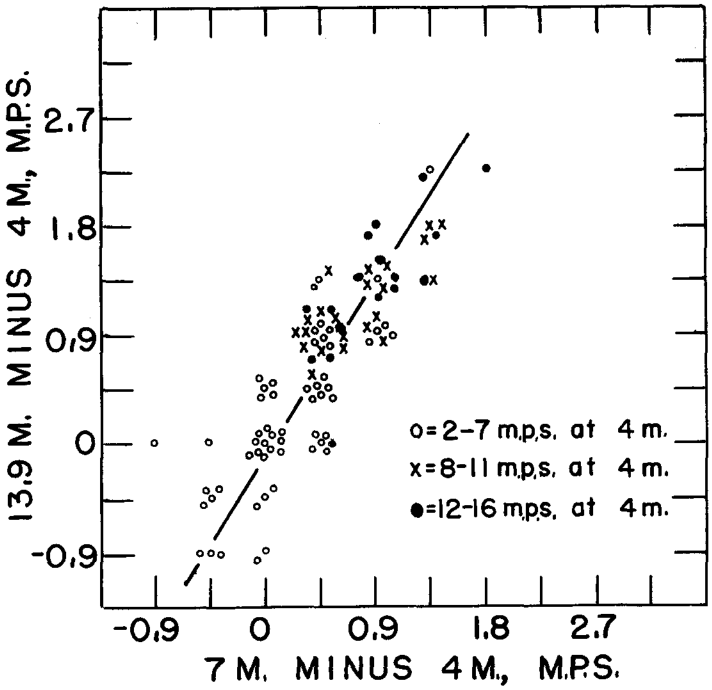

FIGURE 6.—Individual hourly differences in speed in the height interval 4.0–13.9 m. for fair-weather east winds.

One of the first characteristics noted in the profiles is the similarity between daytime and nighttime periods in most cases. This suggests that diurnal stability variations play a less important role in such an exposure than in plains and valleys.

The profiles for the rainy periods are shown in figure 4. In this classification, prevailing directions were west 50 percent, southwest 48 percent, and northwest 2 percent. Stratification into west and southwest directions showed no significant differences. The profiles are observed to have a greater slope than those of fair-weather west and east winds, and to have a curvature which is concave to the speed axis in the 2.4- to 7-m. height interval.

Figures 2–4 present mean profiles, but it is also desirable to illustrate the scatter about the mean. A test of this was arranged by tabulating the hourly differences in speed between 4 m. and 7 m. and between 4 m. and 13.9 m. These tabulations, along with the speed at 4 m., of course, represent the individual hourly profiles between 4 m. and 13.9 m. Figure 5 is a scatter diagram of these differences for the fair-weather west winds. The regression line is drawn by the graphical method. Figure 6 shows a similar plot for the east wind data.

These diagrams can be interpreted as follows. As one moves upward along the regression line, a greater slope (greater gradient in speed) is indicated. At the lower end are a few cases of reversed slope resulting from less speed at 13.9 m and 7 m. than at 4 m. Moving at right angles to the regression line, the area to the left indicates less (concave-upward) curvature in the profile and the area to the right greater curvature. Since the scatter is much larger along the regression line than at right angles to it, it can be seen that the curvature is a more conservative property than the slope.

3. DISCUSSION

If the air stream over the crest had the same structure as that of the free air, implying infinite shear at the ridge line, we would expect to observe a nearly constant speed in the vertical. Even if an extreme shear in the free air is taken, say 5 m.p.s. per 100 m., this would be equivalent to only 0.7-m.p.s. difference in the interval 4 to 13.9 m.; normally it would be much less. This nearly constant speed is only characteristic of the speed class 2–7 m.p.s. in the east winds.

The question naturally arises as to whether or not the observed profile is identical with the fully turbulent logarithmic or power-law profiles, observed over flat terrain under conditions of small temperature gradient. A graph of speed on a linear scale and height on a logarithmic scale should result in a straight-line plot if the data conform to the logarithmic law. Figures 2–4 show that the straight-line relationship does not hold too well,

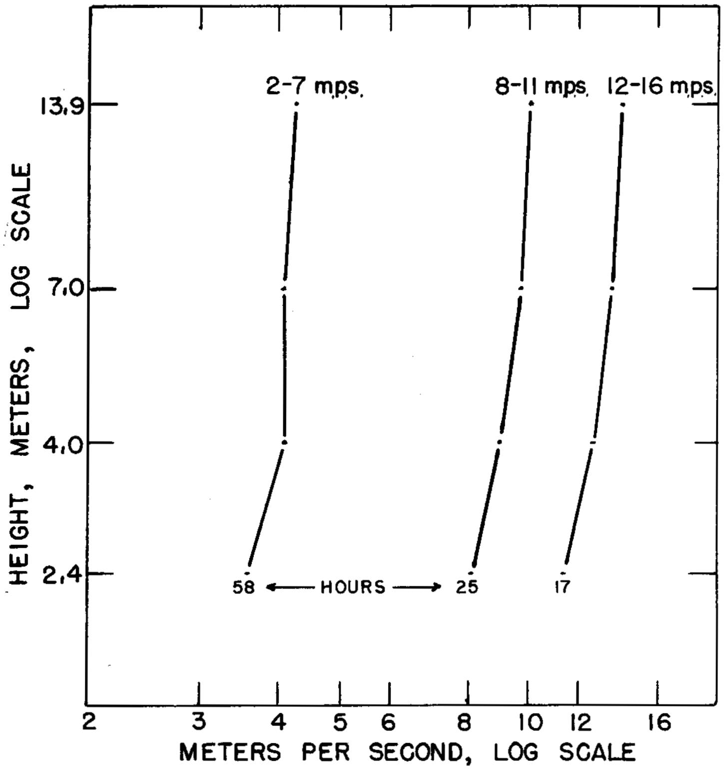

FIGURE 7.—Vertical profiles of east-wind speed at ridge top, on log-log coordinates. Day and night hours are combined.

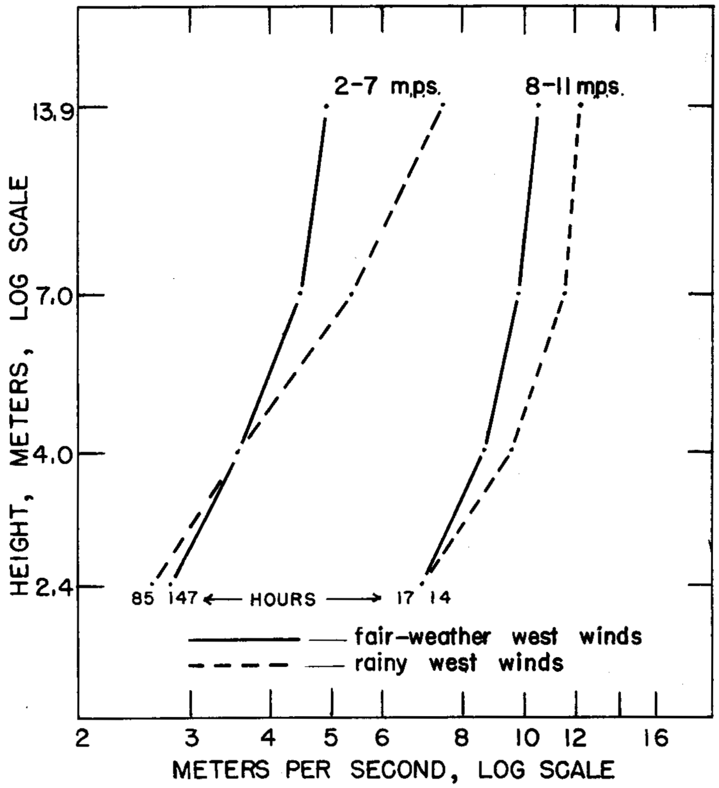

FIGURE 8.—Vertical profiles of west-wind speed at ridge top, on log-log coordinates. Day and night hours are combined.

especially in comparing the 2.4–4-m. layer with the layers above.

The simple form of the logarithmic law assumes a condition of neutral stability and might not be expected to apply to conditions on a ridge top. Theoretical extensions of the law to other conditions of lapse rate show that a profile curve which is convex toward the speed axis, as in figures 2–4, is typical of super-adiabatic lapse rates [3]. This is supported by observations, for example, by Johnson [4]. However, lapse rates on the ridge, if not neutral, would be expected to occur more frequently in the stable category than in the unstable one, favoring a profile concave toward the speed axis. Most of the profiles in figures 2–4 are convex toward the speed axis.

A power law has been found to fit observed data by several investigators. DeMarrais [5] has presented a comparison of the logarithmic and power laws in layers above the lowest few meters. His results favor the power law. It is usually expressed as

$$u=u_1\left(\frac{z}{z_1}\right)^a$$

where u_1 is a given speed at height z_1; the exponent a is assigned values appropriate to a particular investigation and is shown to vary with stability and other factors. A plot of log u against log z should result in a straight line if the power law holds. The factor a must be constant with height in order for a straight-line plot to result. The changes in the value of a with height which have been determined [5] are very small related to the height interval here, so we should expect a straight-line plot if the wind over the ridge has the same structure as that over flat terrain. Figure 7 shows the data for the east winds plotted on log-log coordinates. Again the straight-line relationship does not hold too well, although the fit is better than in figure 2.

The primary evidence that the profile does not correspond to that over flat terrain is provided by the value of the exponent a. In the layer 4–13.9 m. the mean value of a from figure 7 is near 0.07, a value significantly less than values obtained over flat surfaces, which range from about 0.10 to 0.75. This discrepancy does not appear in such clear-cut fashion in the west wind data nor in the layer 2.4–4 m. in any of the profiles. Within the layer 2.4–4 m., and at times in the layer 4–7 m., the value of a does lie within the range obtained in observations over flat terrain.

In this connection a statement by Rossby and Montgomery [6] is of interest: "It is probable that the z_0 value determining the velocity profile in the first few meters above the surface depends upon the character of the ground within, say, the nearest hundred meters, whereas the z_0 value determining the velocity profile higher up . . . presumably depends on the character of the landscape over a distance of many kilometers." Rossby and Montgomery supposed that the adjustment of the mixed layer's depth to the effect of varying roughness is rapid. It appears quite possible that an air stream which strikes a rough surface after having been previously *above* the surface boundary layer requires some period of time of the order of a few minutes to develop a turbulent profile to the height normally attributed to the surface boundary layer (about 30 m.). If the air stream approaching the slope of the ridge is characterized by vertical shear below the level of the crest and also by converging trajectories toward the crest, then the upper part of the current would not have been in contact with the ground surface in its immediate history. The lower part may have had only a short fetch of some tens of meters over the ground surface. There may then be insufficient time for the turbulent profile to develop to its full extent by the time it moves over the crest. It is suggested that this is the explanation of the different characteristics of the lower and upper parts of the 13.9-m profile.

Knowledge of the profile of the incoming wind in a deep layer upstream, along with temperature lapse-rate conditions, would be necessary for establishing definitely the nature of the effect of the ridge. It appears quite possible that some of the characteristics of the profiles could be explained by a jet over the ridge, or that the vertical gradient of speed represents a simple barrier—or obstacle—effect. With either of these cases as a *unique* explanation, however, one should expect to observe a profile which is concave to the speed axis.

REFERENCES

1. W. E. K. Middleton, *Meteorological Instruments*, 2d ed. rev., University of Toronto Press, Toronto, 1943.
2. S. P. Fergusson, "Experimental Studies of Anemometers," *Harvard Meteorological Studies* No. 4, Harvard Univ. Press, Cambridge, Mass., 1939.
3. O. G. Sutton, *Micrometeorology*, McGraw-Hill Book Co., New York, N.Y., 1953, 333 pp.
4. O. Johnson, "An Examination of the Vertical Wind Profile in the Lowest Layers of the Atmosphere," *Journal of Meteorology*, vol. 16, No. 2, Apr. 1959, pp. 144–148.
5. G. A. DeMarrais, "Wind-Speed Profiles at Brookhaven National Laboratory," *Journal of Meteorology*, vol. 16, No. 2, Apr. 1959, pp. 181–190.
6. C. G. Rossby and R. B. Montgomery, "The Layer of Frictional Influence in Wind and Ocean Currents," Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, *Papers in Physical Oceanography and Meteorology*, vol. 3, No. 3, 1935.